Seismic Performance Assessment of Buildings Located on Hillside Slope

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ABSTRACT: In the seismically active Indian Himalayan region, lack of available flat lands and ever-increasing housing needs have led to widespread construction of multi-storey reinforced concrete moment frame buildings on hilly slopes. Such buildings have foundation at different levels and columns of varying height to accommodate ground slope, introducing stiffness irregularity over the height of the structure. During an earthquake, this can lead to stress concentration in structure and may make them more vulnerable to collapse as compared to their regular counterparts. The primary objective of this study is to evaluate the seismic performance and factors influencing collapse capacity of buildings on hilly slopes designed as per modern Indian seismic building codes, which is not extensively investigated in past. To this end, two-dimensional numerical building models capable of simulating flexural and shear failure are created in OpenSEES for modern Indian seismic code compliant reinforced concrete special moment resisting frames located in city of Aizwal in the Himalayan region of India. The collapse capacity of the nonlinear building models is evaluated using incremental dynamic analysis for a suite of site specific ground motions. The seismic collapse fragility curves are developed as a metric to assess the seismic vulnerability of buildings. Buildings located on slope have lower median collapse capacity as compared to buildings located on flat grounds. The seismic response of buildings located on slope is particularly influenced by type of configuration and building height. The median collapse capacity *[Sa(T=1s)]* decreases by 20% to 42% with increase in slope angle from 5° to 30° as compared to building on no slope.

1. INTRODUCTIONS

The Himalayan region in North to North-East India has very high seismicity due to several active faults created by movement of Indo-Australian Plate against the Eurasian Plate. Due to active seismicity in the region, the built environment in North-East India is exposed to moderate and large magnitude earthquakes such as, Kashmir (M_w 7.6, 2005) and Sikkim (M_w 6, 2011) and Gorkha (M_w 7.8, 2015). These earthquakes have resulted in extensive loss to life and property. For instance, 2015 Gorkha earthquake caused extensive damage to 256,697 houses and complete destruction of 98,852 houses (Varum et al. 2018). The North-East India is typically a hilly terrain. To meet the housing demands of increasing population and due to shortage of flat lands, buildings are often constructed on sloping grounds (Surana et al. 2018). To accommodate sloping ground profile, buildings foundations rest at different levels and have columns of varying heights, giving rise to vertical irregularity over the height of the structure. Varying column heights at same floor level due to presence of sloping grounds also results in shifting of center of stiffness away from center of mass, introducing torsional effects in buildings. Therefore, for buildings constructed on hilly slopes, the seismic response of buildings is greatly affected by the presence of stiffness irregularity along the slope and across the slope of the hill. The present study focusses on seismic performance of buildings influenced by stiffness irregularity along slope direction only, the torsion due to irregularity in the cross slope direction is not considered. Recent studies have observed higher seismic fragility of buildings located on hill slopes as compared to the regular building counterparts located on flat ground (Surana et al. 2018; Wang et al. 2014). Singh et al. (2012) analyzed the seismic behavior of two typical stepping back configurations of hill buildings using linear and nonlinear time history analyses and observed that the story at higher ground level in building located on hill slope is most susceptible to damage. Mohammad et al. (2017) employed equivalent static approach and response spectrum method to study seismic behavior of few building configurations of hill buildings. They concluded that to ascertain true behaviour of hill buildings, equivalent static method entirely depended on time period is not adequate. Surana et al. (2018) have considered the influence of Indian seismic design codal level (buildings constructed before 1962, and after 2002 high-code) on response of low and mid-rise buildings with different configurations located on hill slope. They observed 50% and 10% reduction in median collapse capacity of pre-code and high-code hill buildings when compared to their flat-terrain counterparts due to torsional irregularity and shear failure of short columns.

This paper extends on previous research studies by assessing the impact of different building parameters on seismic collapse capacity of modern code-compliant reinforced concrete special moment resisting frames that are located on hilly slopes. The archetype buildings are analytically modelled as a two dimensional frame with lumped plasticity beam column elements with elastic joint shear springs. The rotational plastic hinges provided at beams ends are capable of simulating strength and stiffness deterioration under cycles of earthquake loading. The sloping ground also results in presence of short columns that are susceptible to shear failure. To capture this failure, shear springs capable of simulating direct shear failure and flexure shear failure are provided on top of short columns. The seismic vulnerability of the buildings is quantified through collapse fragility curves that are developed from incremental dynamic analysis on the building models. To evaluate the parameters influencing the collapse capacity of buildings due to stiffness irregularity along slope direction, this study considers archetype buildings located on varying ground slope angle ranging from 0º to 30º, different building configuration and different building heights.

2. SEISMIC COLLAPSE ASSESSMENT METHODOLOGY

Seismic collapse capacity of a structure is a measure the life safety provided by the structure and can be quantified using collapse fragility curves that relate the probability of collapse to different intensities of seismic excitation. This study utilizes collapse fragility curve parameters for assessing the relative vulnerability of buildings and evaluates the impact of different building parameters that affect its response. Seismic collapse fragility curves are developed using incremental dynamic analysis (IDA) conducted on analytical nonlinear models of archetype modern code compliant reinforced concrete moment frame buildings located in the region. The subsequent sections will discuss the methodology in detail.

2.1. Archetypical Building Model

In urban India, most of the residential buildings have the ground story height, intermediate story height and bay width in the range of 3.5 m to 4.5 m, 2.7 m to 3.5 m and 3 m to 5 m respectively (Agarwal et al. 2002). This data serves as basis for development of archetype building for reinforced concrete moment frame buildings. The archetype building represents the generalized structural performance of full class of buildings. The primary archetypical building (Type I, ID1) considered in this study is a three bay four story reinforced concrete moment frame residential building located on flat ground with 3 m floor height and 5 m bay width (Figure 1(a)). To accommodate the gradual and steep hill slope, the primary archetype building is modified only at its foundation level, as shown in Figure 1(b) and

Figure 1(c) respectively. Foundation is not provided at ground level due to sloping ground. Instead a pedestal, generally 1m long, is provided below the ground to the top of footing that introduces a short column in the structure. When the slope of ground is less than or equal to 30º with horizontal, it is termed as gradual slope (Type II, ID2), otherwise it is considered as steep slope (Type III, ID3). For the buildings located on hill slopes, the number of stories are computed by considering stories above the uppermost ground level. This is in line with the recommendation of the Indian seismic code (IS 1893:2002) for calculating approximate fundamental natural period of vibration to compute the design base shear. Thus, the base shear will be same for all structures with same number of stories above uppermost ground level.

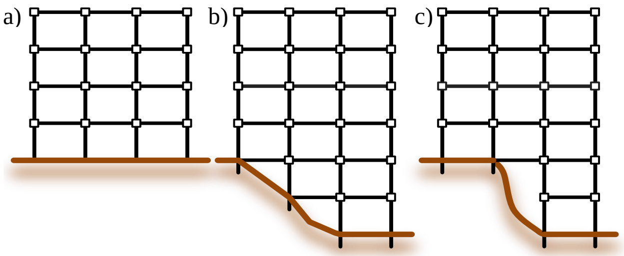

Figure 1: The geometric configuration of archetype buildings located on (a) flat ground (Type I, ID1), (b) gradual slope (Type II, ID2), and (c) steep slope (Type III, ID3)

To assess the influence of ground slope angle on the seismic collapse vulnerability of building, the study also considers additional building configurations located on gradual slope angle of 0º (ID4), 5º (ID5), 10º (ID6), 15º (ID7), 20º (ID8), and 25º (ID9) as shown in Figure 2, along with 30º slope angle (ID2). To accommodate the slope angle, two additional stories will need to be accommodated below the uppermost ground level, as shown in Figure 2 (a). The residential building in North-East India usually ranges from two to six stories. To study the influence of building height on seismic response, buildings with two story (ID10), four story (ID2), and six story (ID11) are considered to be located on the gradual slope. All the building configurations from ID1 to ID11 are designed individually as special reinforced concrete moment-resisting frame according to the provisions of strength, stiffness, and detailing requirements from the Indian Standard codes (IS 1893:2002, IS 13920:1993). They are assumed to be located in the North-Eastern Indian city of Aizwal, located in the highest seismic zone V as per Indian seismic code IS 1893(2002). The buildings are considered as residential buildings and are designed to withstand dead and live loads recommended by IS 875:1987. The building design considers M25 grade concrete (f_{ck} = 25MPa) and Fe415 (f_y = 415 MPa) steel with maximum percentage of tension and compression reinforcement in beams is restricted to 1.5% each and total longitudinal reinforcement in columns is limited to 3%. The columns and beam have a width of 300 mm with depth of column range from 350 to 450 mm and for beams 350 to 400 mm.

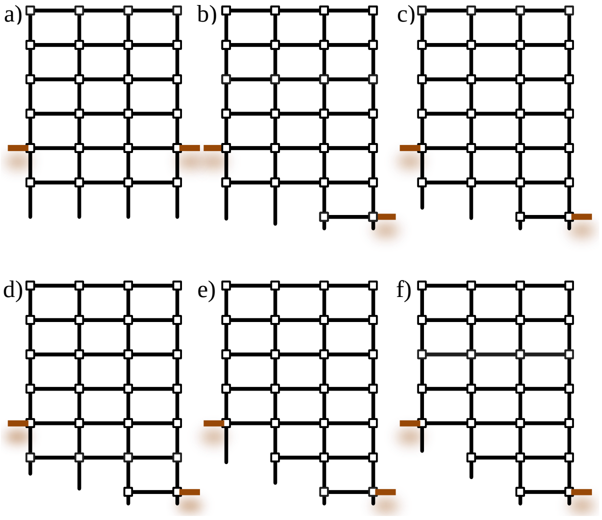

Figure 2: The geometric configurations of archetype buildings located on ground with slope angle (a) 0º (ID4), (b) 5º (ID5), (c) 10º (ID6), (d) 15º (ID7), (e) 20º (ID8), and (f) 25º (ID9)

2.2. Nonlinear Building Model

The archetypical buildings are modelled as two-dimensional frame with lumped plasticity beam-column elements and elastic joint shear springs in OpenSEES (2018). The beam and columns are modelled using elastic beam-column elements with inelastic rotational springs at the ends. The inelastic springs are modeled using hysteretic material developed by Ibarra et al. (2005) that captures deterioration of flexural strength and stiffness over cycles of loading. The inelastic springs have a trilinear backbone curve that captures the negative stiffness of post-peak response enabling the modeling of the strain-softening behavior caused due to concrete crushing, rebar buckling and fracture, and bond failure (Haselton et al. 2008). The study uses the plastic-hinge parameters defined by empirical equations developed by Haselton et al. (2008) based on experimental test results of over 200 columns. The plastic hinge properties are based on beam-column properties such as, section size, longitudinal steel yield strength and area, shear reinforcement spacing, concrete compressive strength and axial load in column. To capture the flexural response, the flexural springs are provided in zero length elements at both at top and bottom of all elastic beam-column elements (Figure (a)). Generally, to accommodate the ground slope profile, short columns are provided at lower stories that are susceptible to shear failure in addition to flexural failure. To model the nonlinear behavior of these columns, shear springs in addition to flexural springs are provided in the zero length element on top of the column, as illustrated in Figure 3(b).

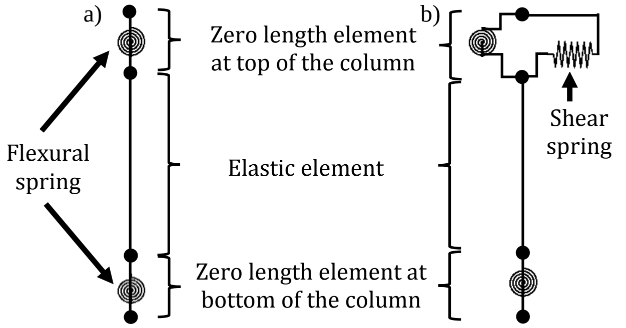

Figure 3: Lumped plasticity model for the (a) regular columns, and (b) short columns

The shear spring is modelled using uniaxial material in OpenSEES (2018), such that column response will be controlled by flexural inelastic springs until shear failure occurs. The shear spring tracks the response of the associated beam-column element until it crosses the pre-defined shear limit curve corresponding to direct shear failure (Sezen and Moehle 2004) and flexural shear failure (Elwood 2004). Once the shear limit curve is reached, the properties of the shear spring is updated to represent the expected negative shear stiffness of for the column. The RC beam-column joint is modelled in OpenSEES (2018) by using joint2D element with elastic joint shear spring to model joint panel shear behavior. To model the rotational flexibility of the footing, elastic semi-rigid rotational springs are provided at each column base.

2.3. Ground Motions

To account for spectral shape of expected ground motions in Aizwal, site specific ground motions based on uniform hazard spectra for the city are selected. The uniform hazard spectra with 2% probability of exceedance in 50 years is developed based on probabilistic seismic hazard assessment for India by Nath and Thingbaijam (2012). Based on the uniform hazard spectra, 30 far-field ground motions are selected from PEER-NGA (2018) database. The mean response spectra of the selected ground motions matches the uniform hazard spectra for the site closely and the same is illustrated in Figure 4. Thirty selected ground motion records have magnitude (M_w) greater ≥ 6.5 and average shear wave velocity for upper 30 m soil column (V_{S30}) ranging from 360 and 760 m/s.

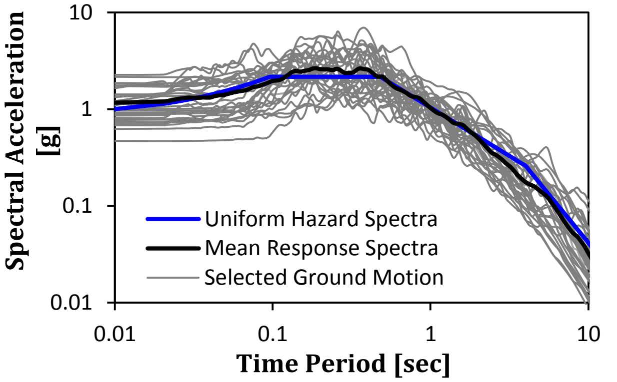

Figure 4: Site specific ground motions selected based on uniform hazard spectra for Aizwal, India.

2.4. Incremental Dynamic Analysis

Incremental dynamic analysis (IDA) is conducted on nonlinear structural models to assess its seismic collapse capacity. In incremental dynamic analysis (IDA), nonlinear model of the building is subjected to increasing intensities of same ground motion, until it collapses (Vamvatsikos and Cornell, 2002). The process begins by subjecting the structure to a ground motion and recording its structural response. The ground motion time history is then scaled up and the structural response is recorded. This process of scaling the ground motion and recording the response is continued until the structure experiences dynamic structural instability due to sidesway collapse as indicated by large interstory drift ratios. The collapse capacity of the structure for a ground motion is measured using intensity of scaled ground motion that causes the collapse of the structure. The IDA results are represented using IDA curves, illustrating the variation of ground motion intensity measure (*IM*, e.g., spectral acceleration, *Sa*) with structural response or engineering demand parameter (*EDP* e.g., interstory drift ratio). Figure 5 illustrates variation in collapse capacity of a four story building located on flat ground (ID1) when subjected to 30 ground motions records selected in Section 2.3. Generally the spectral acceleration at fundamental period is used as ground motion intensity measure in IDA, but in the present study different building configurations have different fundamental period but closer to 1s. Spectral acceleration at *T*=1s, *Sa(T=1s)*, is used as ground motion *IM* in IDA to compare the collapse capacities of different buildings.

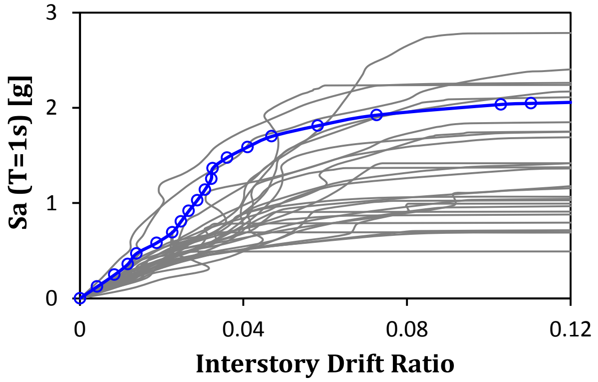

Figure 5: IDA results for a four story building located on flat surface (ID1) using 30 ground motions. The blue line shows IDA results for a single ground motion till structural collapse.

3. RESULTS

In present study, the seismic collapse capacity of 11 archetype modern reinforced concrete moment frames in Section 2.1 is evaluated through IDA of analytical nonlinear models of the building. IDA is carried out on ach building model using 30 ground motions selected in Section 2.3 and collapse fragility curves are calculated. The collapse fragility curves quantify the probability of collapse at a given intensity of ground motion. Since collapse capacities generally follow a lognormal distribution, the collapse fragility curve is quantified using a lognormal cumulative distribution function (Figure 6). The collapse fragility curves are characterized by two parameters, (a) median collapse capacity (x_m), calculated as the ground motion *IM* corresponding to 50% probability of collapse of structure and, (b) lognormal standard deviation (β) that measures the dispersion in collapse capacity. The lognormal standard deviation (β) in this study corresponds to variability in ground motion characteristics, also known as record to record variability. A summary of fundamental time period, median collapse capacity (x_m), and lognormal standard deviation (β) corresponding to collapse capacity *[Sa(T=1s)]* of all the building configurations is presented in Table 1.

Table 1: Summary of seismic collapse capacity of all the building configurations

ID	*No. of story*	T_1 *[s]*	$x_m{}^*$, *Sa(T=1) [g]*	β^{**}	$x_m{}^*$, *Sa*(T_1) *[g]*
ID1	*4*	*1.07*	*1.32*	*0.45*	*1.24*
ID2	*4*	*1.16*	*0.93*	*0.42*	*0.80*
ID3	*4*	*1.14*	*1.25*	*0.42*	*1.09*
ID4	*4*	*1.51*	*1.60*	*0.51*	*1.09*
ID5	*4*	*1.61*	*1.28*	*0.56*	*0.84*
ID6	*4*	*1.55*	*1.09*	*0.51*	*0.73*
ID7	*4*	*1.45*	*1.05*	*0.47*	*0.71*
ID8	*4*	*1.49*	*1.04*	*0.55*	*0.71*
ID9	*4*	*1.34*	*0.94*	*0.50*	*0.68*
ID10	*2*	*0.75*	*0.68*	*0.41*	*0.85*
ID11	*6*	*1.54*	*1.03*	*0.51*	*0.70*

$^*x_m$ indicates median collapse capacity

$^{**}\beta$ indicates lognormal standard deviation of x_m*, *Sa(T=1)*

The fundamental time period of vibration calculated by modal analysis of cracked sections in OpenSEES (2018) is also presented in Table 1. The study specifically looks at the impact of different configurations, building heights and angle of sloping ground on collapse capacity of vertically irregular structures and the same is discussed in detail in the following sections.

3.1. Influence of building configuration

Firstly, the collapse capacity of common vertically irregular configuration for buildings located on sloping grounds is investigated. The modern reinforced concrete moment frame archetypical buildings located on flat (Type I, ID1), gradual (Type II, ID2) and steep slope (Type III, ID3) are considered. As evident in Table 1, buildings located on sloping ground (ID2 and ID3) have higher time period and hence flexible as compared to those located on flat ground (ID1). The comparison of collapse fragility curves of four story buildings located on flat (Type I, ID1), gradual (Type II, ID2), and steep slope (Type III, ID3) is shown in Figure 6.

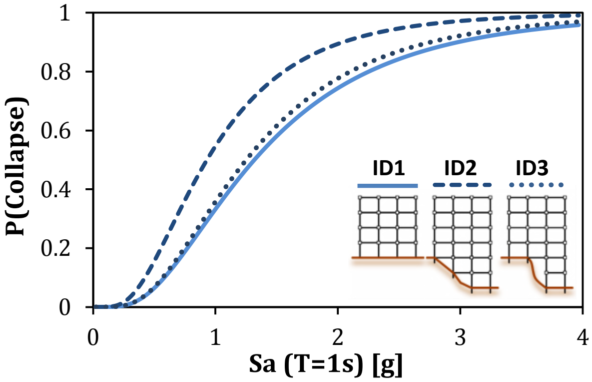

Figure 6: Comparison of collapse fragility curves of four story archetype building located on flat (ID1), gradual (ID2), and steep slope (ID3)

The buildings located on flat surface (ID1) have median collapse capacity (*Sa(T=1s)*) 29.5% and 5.3% higher than those located on gradual (ID2) and steep (ID1) slope building respectively, indicating higher collapse vulnerability of buildings located on sloping grounds. This is mainly due column failure from increased stress concentration introduced by irregularity over height of the buildings. In Type I buildings, flexural failure of columns is responsible for structural collapse and for Type II and Type III buildings collapse occurs due to the combination of column flexure and short columns shear failure.

3.2. Influence of ground slope angle

The four story buildings located on gradual slope have median collapse capacity (*Sa(T=1s)* 25.6% lower than buildings located on steep slope. To understand the effect of gradual slope angles on collapse capacity, additional four story buildings with two stories below the uppermost ground level located on 0° (ID4), 5° (ID5), 10° (ID6), 15° (ID7), 20° (ID8), 25° (ID9), and 30° (ID2) are considered as shown on Figure 2 and results are summarised in Table 1. It is observed that the median collapse capacity *[Sa(T=1s)]* decreases with increase in slope angle, indicating strong correlation between slope angle of the ground and collapse vulnerability of buildings, that structure is more vulnerable to collapse as seen in Figure 7.

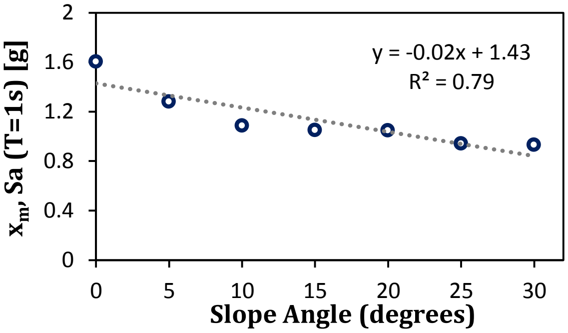

Figure 7: Comparison of median collapse capacity (Sa(T=1s) of four story building with varying ground slope angle

It is evident from Figure 2, that the building can have lowermost column with heights varying from 1m to 3.6m to accommodate the ground slope angle. Depending on the slope angle the number of columns below the uppermost ground level also varies. For shorter columns, the failure mode changes from flexure to flexure shear. The predominant failure mechanism generally observed in buildings located on slope is shown Figure 8. The red circles indicates failure. In ID5 (5° slope angle) building, the building collapse is due to flexural failure of columns where else in ID2 (30° slope angle) the failure is localized due to shear failure of short columns. The decrease in median collapse capacity of structure with increase in slope angle is evident from the comparison of collapse fragility curves shown in Figure 9.

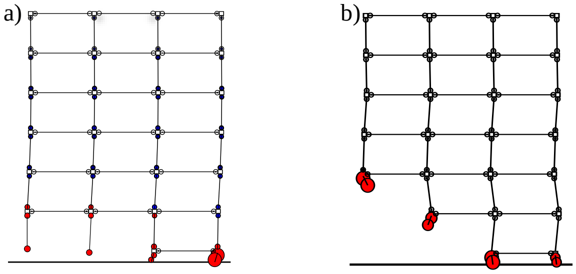

Figure 8: Predominant collapse mechanisms for the four story archetype building located on hill slope with a) 5º (ID5), and b) 30º (ID2) slope angle

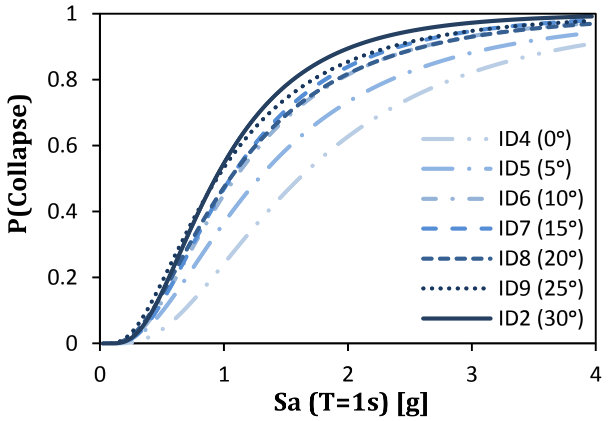

Figure 9: Comparison of collapse fragility curves of four story archetype building located on ground with slope angle 0º (ID4), 5º (ID5), 10º (ID6), 15º (ID7), 20º (ID8), 25º (ID9), and 30º (ID2)

3.3. *Influence of building height*

To assess the influence of building height on the seismic collapse vulnerability, present study considers two, four, and six story modern reinforced concrete moment frame archetypical buildings located on gradual slope. Here, the number of stories are calculated by considering stories above the uppermost ground level. Each building has two stories below the uppermost ground level to accommodate the gradual slope. As seen in Table 1, the fundamental period of the building increases with increase in height due to increase in flexibility. The comparison of collapse fragility in Figure 10 illustrates the increase in median collapse capacity of structure with increase in building height. The median collapse capacity *[Sa(T_1)]* decreases with increasing height of the building which is in line with the past research studies. But to compare the response among buildings, spectral acceleration at *T=1s* is considered. The six and four story buildings located on gradual slope have median collapse capacity *[Sa(T=1s)]* 36.8% and 51.5% higher than the two story building respectively.

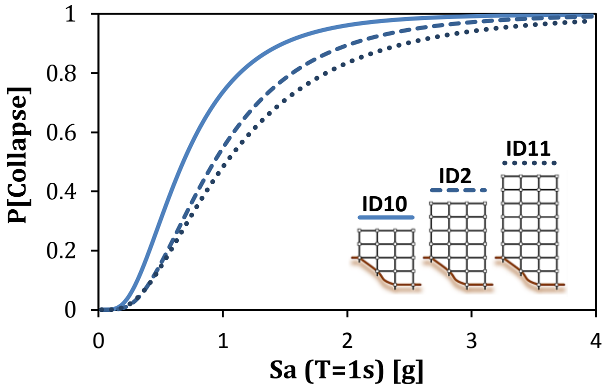

Figure 10: Comparison of collapse fragility curves of two story (ID10), four story (ID2) and six story (ID11) archetype building located on gradual slope

4. CONCLUSIONS AND FUTURE WORK

This study evaluates the seismic collapse capacity of the archetypical modern Indian code-compliant reinforced concrete moment frame buildings located on sloping and flat grounds using Performance Based Earthquake Engineering (PBEE) framework. Thirty site specific ground motions are selected based on uniform hazard spectra for the Aizwal city to carry out the IDA. It is evident from the findings of present study that ground slope, type of configuration, and building height greatly affects the seismic response of a modern code designed special moment frame building. Based on median collapse capacity, it is observed that the buildings located on steep and gradual slope have median collapse capacity (*Sa(T=1s)*, 5.3% to 29.5% lower than their counterparts located on flat grounds. Moreover, for buildings located on gradual slope, with increase in slope angle from 5º to 30º the median collapse capacity (*Sa(T=1s)* decreases by 20% to

42% as compared to building on 0° slope (ID4). For buildings located on gradual slope the median collapse capacity *[Sa(T=1s)]* increases with increase in building height, with 36.8% increase from two story to four story and 10.8% increase from four story to six story. The present study considers the influence of independent building parameters. In future studies, combined effect of these parameters in predicting seismic collapse capacity of modern reinforced concrete moment frame buildings located in hilly regions of India will be evaluated.

5. ACKNOWLEDGEMENT

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